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The hidden charm decay of $Y(4140)$ by the rescattering mechanism

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ABSTRACT

Assuming that $Y(4140)$ is the second radial excitation of the P-wave charmonium χ''_{cJ} $(J = 0, 1)$, the hidden charm decay mode of $Y(4140)$ is calculated in terms of the rescattering mechanism. Our numerical results show that the upper limit of the branching ratio of the hidden charm decay $Y(4140) \to J/\psi\phi$ is on the order of 10^{-4}–10^{-3} for both of the charmonium assumptions for $Y(4140)$, which disfavors the large hidden charm decay pattern indicated by the CDF experiment. It seems to reveal that the pure second radial excitation of the P-wave charmonium χ''_{cJ} $(J = 0, 1)$ is problematic.

Recently, the CDF experiment announced a new narrow state named $Y(4140)$ by studying the $J/\psi\phi$ mass spectrum in the exclusive $B^+ \to J/\psi\phi K^+$ process. Its mass and decay width are $M = 4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst})\ \text{MeV}/c^2$ and $\Gamma = 11.7^{+8.3}_{-5.0}(\text{stat}) \pm 3.7(\text{syst})\ \text{MeV}/c^2$, respectively [1].

The charmonium-like states discovered in the past six years include $X(3872)$, $X(3940)/Y(3930)/Z(3930)$, $Y(4260)$, $Z(4430)$, etc. The observation of $Y(4140)$ not only increases the spectrum of charmonium-like state, but also helps us to further clarify these observed charmonium-like states.

In our recent work [2], we discussed the various possible interpretations of the $Y(4140)$ signal. We concluded that $Y(4140)$ is probably a $D_s^*\bar{D}_s^*$ molecular state with $J^{PC} = 0^{++}$ or 2^{++}, while $Y(3930)$ is its $D^*\bar{D}^*$ molecular partner, as predicted in our previous work [3]. Later, the author of Ref. [4] also agreed with the explanation of the $D_s^*\bar{D}_s^*$ molecular state for $Y(4140)$ and claimed that hybrid charmonium with $J^{PC} = 1^{-+}$ cannot be excluded. In Ref. [5], they used a molecular $D_s^*\bar{D}_s^*$ current with $J^{PC} = 0^{++}$ and obtained $m_{D_s^*\bar{D}_s^*} = (4.14 \pm 0.09)$ MeV, which can explain $Y(4140)$ as a $D_s^*\bar{D}_s^*$ molecular state. The author of Ref. [6] also used the QCD sum rules to study $Y(4140)$ and came to a different conclusion than that in [5].

As indicated in our work [2], the study of the decay modes of $Y(4140)$ is important to test the molecular structure $D_s^*\bar{D}_s^*$ of $Y(4140)$. Assuming $Y(3940)$ and $Y(4140)$ as $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$ molecular states, respectively, the authors of Ref. [7] calculated the strong decays of $Y(4140) \to J/\psi\phi$ and $Y(3940) \to J/\psi\omega$ and the radiative decay $Y(4140)/Y(3940) \to \gamma\gamma$ by the effective Lagrangian approach. The result of the strong decays of $Y(3940)$ and $Y(4140)$ strongly supports the molecular interpretation for $Y(3940)$ and $Y(4140)$.

On the other hand, studying the decay modes with other structure assignments for $Y(4140)$ will help us to understand the character of $Y(4140)$ more accurately. Along this line, we further calculate the hidden charm decay mode of $Y(4140)$ assuming it to be a conventional charmonium state by the rescattering mechanism [8,9].

If $Y(4140)$ is a conventional charmonium state, $Y(4140)$ should be the second radial excitation of the P-wave charmonium χ''_{cJ} [2]. Its quantum number should be $J^P = 0^+, 1^+, 2^+$. Since the rather small Q-value for the decay $B^+ \to K^+Y(4140)$ favors a low angular momentum ℓ between K^+ and $Y(4140)$ more, $Y(4140)$ thus favors a low quantum number J due to $J = \ell$. In the following, we focus on the hidden charm decay of $Y(4140)$ with χ''_{c0} $(J^P = 0^+)$ and χ''_{c1} $(J^P = 1^+)$ assumptions.

For the case where $Y(4140)$ is χ''_{c0}, the hidden charm decay $Y(4140) \to J/\psi\phi$ occurs only through $D_s^+D_s^-$ rescattering, which is depicted in Fig. 1. If $Y(4140)$ is χ''_{c1} with $J^P = 1^+$, $Y(4140) \to J/\psi\phi$ occurs only via $D_s^+D_s^{*-}$ + h.c. rescattering, which is shown in Fig. 2.

In Refs. [10–12], the effective Lagrangians, which are relevant to the present calculation, are constructed based on chiral symmetry and heavy quark symmetry:

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$$\mathcal{L}_{0^+DD} = g_Y Y D_s^+ D_s^-, \tag{1}$$

$$\mathcal{L}_{1^+DD} = g_Y Y^\mu \big[D_s^+ D_s^{*-}{}_\mu - D_s^- D_s^{*+}{}_\mu \big], \tag{2}$$

$$\mathcal{L}_{J/\psi\mathcal{D}\mathcal{D}} = i g_{J/\psi\mathcal{D}\mathcal{D}} \psi_\mu \big(\partial^\mu \mathcal{D}\mathcal{D}^\dagger - \mathcal{D}\partial^\mu \mathcal{D}^\dagger \big), \tag{3}$$

$$\mathcal{L}_{J/\psi\mathcal{D}^*\mathcal{D}} = -g_{J/\psi\mathcal{D}^*\mathcal{D}} \varepsilon^{\mu\nu\alpha\beta} \partial_\mu \psi_\nu \big(\partial_\alpha \mathcal{D}_\beta^* \mathcal{D}^\dagger + \mathcal{D}\partial_\alpha \mathcal{D}_\beta^{*\dagger} \big), \tag{4}$$

$$\begin{aligned} \mathcal{L}_{J/\psi\mathcal{D}^*\mathcal{D}^*} = -i g_{J/\psi\mathcal{D}^*\mathcal{D}^*} \big\{ & \psi^\mu \big(\partial_\mu \mathcal{D}^{*\nu} \mathcal{D}_\nu^{*\dagger} - \mathcal{D}^{*\nu} \partial_\mu \mathcal{D}_\nu^{*\dagger} \big) \\ & + \big(\partial_\mu \psi_\nu \mathcal{D}^{*\nu} - \psi_\nu \partial_\mu \mathcal{D}^{*\nu} \big) \mathcal{D}^{*\mu\dagger} \\ & + \mathcal{D}^{*\mu} \big(\psi^\nu \partial_\mu \mathcal{D}_\nu^{*\dagger} - \partial_\mu \psi_\nu \mathcal{D}^{*\nu\dagger} \big) \big\}, \end{aligned} \tag{5}$$

$$\mathcal{L}_{\mathcal{D}\mathcal{D}\mathbb{V}} = -i g_{\mathcal{D}\mathcal{D}\mathbb{V}} \mathcal{D}_i^\dagger \overleftrightarrow{\partial}_\mu \mathcal{D}^j \big(\mathbb{V}^\mu \big)^i_j, \tag{6}$$

$$\mathcal{L}_{\mathcal{D}^*\mathcal{D}\mathbb{V}} = -2 f_{\mathcal{D}^*\mathcal{D}\mathbb{V}} \varepsilon_{\mu\nu\alpha\beta} \big(\partial^\mu \mathbb{V}^\nu \big)^i_j \big(\mathcal{D}_i^\dagger \overleftrightarrow{\partial}^\alpha \mathcal{D}^{*\beta j} - \mathcal{D}_i^{*\beta\dagger} \overleftrightarrow{\partial}^\alpha \mathcal{D}^j \big), \tag{7}$$

$$\begin{aligned} \mathcal{L}_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}} = & \, i g_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}} \mathcal{D}_i^{*\nu\dagger} \overleftrightarrow{\partial}_\mu \mathcal{D}_\nu^{*j} \big(\mathbb{V}^\mu \big)^i_j \\ & + 4 i f_{\mathcal{D}^*\mathcal{D}^*\mathbb{V}} \mathcal{D}_{i\mu}^{*\dagger} \big(\partial^\mu \mathbb{V}^\nu - \partial^\nu \mathbb{V}^\mu \big)^i_j \mathcal{D}_\nu^{*j}, \end{aligned} \tag{8}$$

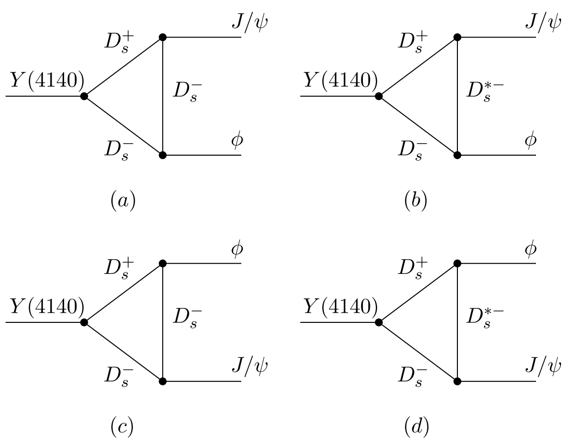

Fig. 1. The diagrams for $Y(4140) \to D_s^+ D_s^- \to J/\psi\phi$ assuming $Y(4140)$ as χ''_{c0} state.

where $\mathcal{D}$ and $\mathcal{D}^*$ are the pseudoscalar and vector heavy mesons, respectively, i.e., $\mathcal{D}^{(*)} = ((\bar{D}^0)^{(*)}, (D^-)^{(*)}, (D_s^-)^{(*)})$. $\mathbb{V}$ denotes the nonet vector meson matrices. The values of the coupling constants are [13] $g_{DDV} = g_{D^*D^*V} = \frac{\beta g_V}{\sqrt{2}}$, $f_{D^*DV} = \frac{f_{D^*D^*V}}{m_{D^*}} = \frac{\lambda g_V}{\sqrt{2}}$, $g_V = \frac{m_\rho}{f_\pi}$, where $f_\pi = 132$ MeV, g_V, β and λ are the parameters in the effective chiral Lagrangian that describes the interaction of the heavy mesons with the low-momentum light vector mesons [12]. Following Ref. [14], we take $g = 0.59$, $\beta = 0.9$ and $\lambda = 0.56$. Based on the vector meson dominance model and using the leptonic width of J/ψ, the authors of Ref. [15] determined $g^2_{J/\psi\mathcal{D}\mathcal{D}}/(4\pi) = 5$. As a consequence of the spin symmetry in the heavy quark effective field theory, $g_{J/\psi\mathcal{D}\mathcal{D}^*}$ and $g_{J/\psi\mathcal{D}^*\mathcal{D}^*}$ satisfy the relations: $g_{J/\psi\mathcal{D}\mathcal{D}^*} = g_{J/\psi\mathcal{D}\mathcal{D}}/m_D$ and $g_{J/\psi\mathcal{D}^*\mathcal{D}^*} = g_{J/\psi\mathcal{D}\mathcal{D}}$ [16].

Since the contributions from Fig. 1(c) and (d) are the same as those corresponding to Fig. 2(a) and (b), respectively, the total decay amplitude of $Y(4140) \to D_s^+ D_s^- \to J/\psi\phi$ can be expressed as

$$\mathcal{M}^{(J^P=0^+)} = 2[\mathcal{A}_{1-a} + \mathcal{A}_{1-b}], \tag{9}$$

where one formulates the amplitudes of $\mathcal{A}_{1-a}$ and $\mathcal{A}_{1-b}$ by Cutkosky cutting rule

$$\begin{aligned} \mathcal{A}_{1-a} = & \frac{1}{2} \int \frac{d^3 p_1}{(2\pi)^3 2E_1} \frac{d^3 p_2}{(2\pi)^3 2E_2} (2\pi)^4 \delta^4 (m_Y - p_1 - p_2) [i g_Y] \\ & \times \big[-g_{J/\psi DD} i (p_1 - q) \cdot \varepsilon_{J/\psi} \big] \big[i g_{DDV} (q + p_2) \cdot \epsilon_\phi \big] \\ & \times \left[\frac{i}{q^2 - m^2_{D_s}} \right] \mathcal{F}^2 \big(m_{D_s}, q^2 \big), \end{aligned} \tag{10}$$

$$\begin{aligned} \mathcal{A}_{1-b} = & \frac{1}{2} \int \frac{d^3 p_1}{(2\pi)^3 2E_1} \frac{d^3 p_2}{(2\pi)^3 2E_2} (2\pi)^4 \delta^4 (m_Y - p_1 - p_2) [i g_Y] \\ & \times \big[i g_{J/\psi DD^*} \epsilon_{\mu\nu\kappa\sigma} \varepsilon^\mu_{J/\psi} (-i) p_1^\nu (-i) q^\sigma \big] \\ & \times \big[-2 i f_{D^*DV} \epsilon_{\rho\delta\alpha\beta} i p_4^\rho \varepsilon_\phi^\delta i \big(p_1^\alpha + q^\alpha \big) \big] \\ & \times \left[-g^{\kappa\beta} + \frac{q^\kappa q^\beta}{m^2_{D_s^*}} \right] \left[\frac{i}{q^2 - m^2_{D_s^*}} \right] \mathcal{F}^2 \big(m_{D_s^*}, q^2 \big). \end{aligned} \tag{11}$$

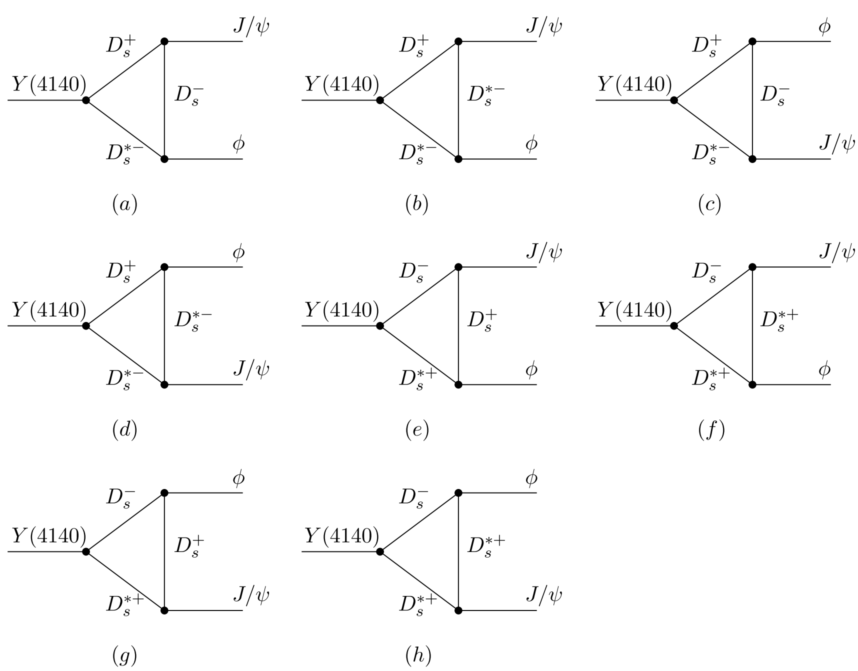

Fig. 2. The diagrams for $Y(4140) \to D_s^+ D_s^{*-} + \text{h.c.} \to J/\psi\phi$ assuming $Y(4140)$ as χ''_{c1} state.

Similarly, we write out the total decay amplitude of $Y(4140) \to D_s^+ D_s^{*-} + D_s^- D_s^{*+} \to J/\psi\phi$

$$\mathcal{M}^{(J^P=1^+)} = 2[\mathcal{A}_{2-a} + \mathcal{A}_{2-b} + \mathcal{A}_{2-c} + \mathcal{A}_{2-d}], \tag{12}$$

where the pre-factor "2" arises from considering that the contribution from $D_s^+ D_s^{*-}$ rescattering is the same as that from $D_s^- D_s^{*+}$ rescattering. The absorptive contributions from Fig. 2(a)–(d) are, respectively,

$$\begin{aligned}
\mathcal{A}_{2-a} = {} & \frac{1}{2}\int \frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2} \\
& \times (2\pi)^4\delta^4(m_Y - p_1 - p_2)[ig_Y \varepsilon_\xi] \\
& \times \big[-g_{J/\psi DD} i(p_1 - q)\cdot\varepsilon_{J/\psi}\big] \\
& \times \big[-2if_{D^*DV}\epsilon_{\mu\nu\alpha\beta} ip_4^\mu \varepsilon_\phi^\nu (iq^\alpha + ip_2^\alpha)\big] \\
& \times \bigg[-g^{\xi\beta} + \frac{p_2^\xi p_2^\beta}{m_2^2}\bigg]\bigg[\frac{i}{q^2 - m_{D_s}^2}\bigg]\mathcal{F}^2\big(m_{D_s}, q^2\big),
\end{aligned} \tag{13}$$

$$\begin{aligned}
\mathcal{A}_{2-b} = {} & \frac{1}{2}\int \frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2} \\
& \times (2\pi)^4\delta^4(m_Y - p_1 - p_2)[ig_Y \varepsilon_\xi] \\
& \times \big[ig_{J/\psi DD^*}\epsilon_{\mu\nu\kappa\sigma}\varepsilon_{J/\psi}^\mu (-i)p_1^\nu (-i)q^\sigma\big] \\
& \times \big\{-g_{D^*D^*V} i(q + p_2)\cdot\epsilon_\phi g_{\alpha\beta} \\
& - 4f_{D^*D^*V}[ip_{4\beta}\epsilon_{\phi_\alpha} - i\epsilon_{\phi_\beta} p_{4\alpha}]\big\} \\
& \times \bigg[-g^{\kappa\beta} + \frac{p_2^\kappa p_2^\beta}{m_2^2}\bigg]\bigg[-g^{\xi\alpha} + \frac{q^\xi q^\alpha}{m_{D_s^*}^2}\bigg] \\
& \times \bigg[\frac{i}{q^2 - m_{D_s^*}^2}\bigg]\mathcal{F}^2\big(m_{D_s^*}, q^2\big),
\end{aligned} \tag{14}$$

$$\begin{aligned}
\mathcal{A}_{2-c} = {} & \frac{1}{2}\int \frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2} \\
& \times (2\pi)^4\delta^4(m_Y - p_1 - p_2)[ig_Y \varepsilon_\xi] \\
& \times \big[g_{DDV} i(q - p_1)\cdot\varepsilon_\phi\big] \\
& \times \big[ig_{J/\psi DD^*}\epsilon_{\mu\nu\alpha\beta}\varepsilon_{J/\psi}^\mu iq^\nu (-i)p_2^\beta\big] \\
& \times \bigg[-g^{\xi\alpha} + \frac{p_2^\xi p_2^\alpha}{m_{D_s^*}^2}\bigg]\bigg[\frac{i}{q^2 - m_{D_s}^2}\bigg]\mathcal{F}^2\big(m_{D_s}, q^2\big),
\end{aligned} \tag{15}$$

$$\begin{aligned}
\mathcal{A}_{2-d} = {} & \frac{1}{2}\int \frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2} \\
& \times (2\pi)^4\delta^4(m_Y - p_1 - p_2)[ig_Y \varepsilon_\xi] \\
& \times \big[-2if_{D^*DV}\epsilon_{\mu\nu\alpha\beta} ip_3^\mu \varepsilon_\phi^\nu i(q^\alpha - p_1^\alpha)\big] \\
& \times \big\{-g_{J/\psi D^*D^*}\big[iq^\kappa \varepsilon_{J/\psi}^\sigma + ip_2^\sigma \varepsilon_{J/\psi}^\kappa \\
& + i(p_2 + q)\cdot\varepsilon_{J/\psi} g^{\kappa\sigma}\big]\big\}\bigg[-g_\kappa^\xi + \frac{p_{2\kappa} p_2^\xi}{m_{D_s^*}^2}\bigg] \\
& \times \bigg[-g_\sigma^\beta + \frac{q_\sigma q^\beta}{m_{D^*}^2}\bigg]\bigg[\frac{i}{q^2 - m_{D_s^*}^2}\bigg]\mathcal{F}^2\big(m_{D_s^*}, q^2\big).
\end{aligned} \tag{16}$$

In the expressions above for the decay amplitudes, form factors $\mathcal{F}^2(m_i, q^2)$, etc., compensate for the off-shell effects of the mesons at the vertices and are written as $\mathcal{F}^2(m_i, q^2) = (\frac{\Lambda^2 - m_i^2}{\Lambda^2 - q^2})^2$, where Λ is a phenomenological parameter. As $q^2 \to 0$, the form factor becomes a number. If $\Lambda \gg m_i$, it becomes unity. As $q^2 \to \infty$, the form factor approaches zero. As the distance becomes very small, the inner structure manifests itself, and the whole picture of hadron interaction is no longer valid. Hence, the form factor vanishes and plays a role in cutting off the end effect. The expression of Λ is defined as $\Lambda(m_i) = m_i + \alpha\Lambda_{\mathrm{QCD}}$ [13]. Here, m_i denotes the mass of exchanged meson, $\Lambda_{\mathrm{QCD}} = 220$ MeV, and α denotes a phenomenological parameter in the rescattering model.

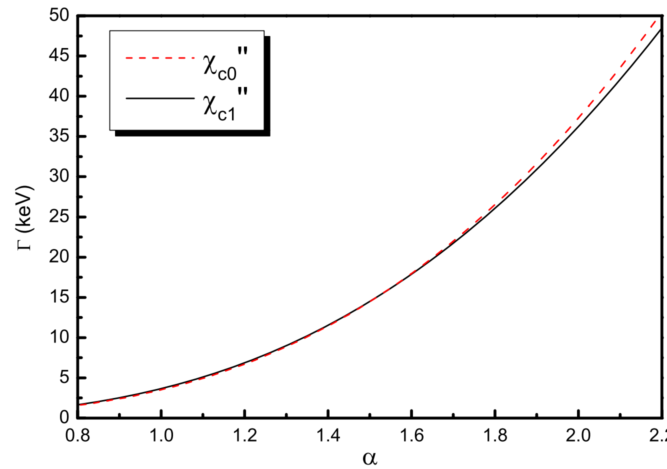

Fig. 3. The variation of $\Gamma[Y(4140) \to J/\psi\phi]$ assuming $Y(4140)$ as χ_{c0}'' and χ_{c1}'' states to α.

By fitting the central value of the total width of $Y(4140)$ (11.7 MeV), we obtain the coupling constant g_Y in Eq. (8)

$$g_Y = \begin{cases} 2.79\ \text{GeV}, & \text{for } \chi_{c0}'', \\ 2.65\ \text{GeV}, & \text{for } \chi_{c1}'', \end{cases}$$

where we approximate $D_s^+ D_s^-$ and $D_s^+ D_s^{*-}$ + h.c. as the dominant decay mode of $Y(4140)$ when assuming $Y(4140)$ to be χ_{c0}'' and χ_{c1}'', respectively. In this way, we can extract the upper limit of the value of the coupling constant g_Y, which further allows us to obtain the upper limit of the hidden charm decay pattern of $Y(4140)$.

The value of α in the form factor is usually of order unity [13]. In this work, we take the range of $\alpha = 0.8$–2.2. The dependence of the decay widths of $Y(4140)(\chi_{c0}'') \to D_s^+ D_s^- \to J/\psi\phi$ and $Y(4140)(\chi_{c1}'') \to D_s^+ D_s^{*-}$ + h.c. $\to J/\psi\phi$ on α is presented in Fig. 3.

In Table 1, we list the typical values of the branching ratios of $Y(4140)(\chi_{c0}'') \to D_s^+ D_s^- \to J/\psi\phi$ and $Y(4140)(\chi_{c1}'') \to D_s^+ D_s^{*-}$ + h.c. $\to J/\psi\phi$ when taking different α.

In summary, in this Letter, we discuss the hidden charm decay of $Y(4140)$ newly observed by the CDF experiment when assuming $Y(4140)$ as χ_{c0}'' and χ_{c1}''.

According to the rescattering mechanism [8,9], the hidden charm decay mode $J/\psi\phi$ occurs via $D_s^+ D_s^-$ and $D_s^+ D_s^{*-}$ + h.c., respectively, corresponding to χ_{c0}'' and χ_{c1}'' assumptions for $Y(4140)$. Our numerical results indicate that the upper limit of the order of magnitude of the branching ratio of $Y(4140) \to J/\psi\phi$ is 10^{-4}–10^{-3} for both of the assumptions for $Y(4140)$, which is consistent with the rough estimation indicated in Ref. [2]. Here $Y(4140)$ lies well above the open charm decay threshold. A charmonium with this mass would decay into an open charm pair dominantly. The branching fraction of its hidden charm decay mode $J/\psi\phi$ is expected to be small.

Such small hidden charm decay disfavors the large hidden charm decay pattern of $Y(4140)$ announced by the CDF experiment [1], which further supports that explaining $Y(4140)$ as the pure second radial excitation of the P-wave charmonium χ_{cJ}'' is problematic [2].

Table 1
The typical values of the branching ratio of $Y(4140) \to J/\psi\phi$ for different α assuming $Y(4140)$ to be χ''_{c0} and χ''_{c1}.

$Y(4140)$	α							
	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2
χ''_{c0}	1.3×10^{-4}	3.0×10^{-4}	5.7×10^{-4}	9.8×10^{-4}	1.5×10^{-3}	2.3×10^{-3}	3.2×10^{-3}	4.3×10^{-3}
χ''_{c1}	1.4×10^{-4}	3.1×10^{-4}	5.9×10^{-4}	9.9×10^{-4}	1.5×10^{-3}	2.2×10^{-3}	3.1×10^{-3}	4.1×10^{-3}

We encourage further experimental measurement of the decay modes of $Y(4140)$, which will enhance our understanding of the character of $Y(4140)$.

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